

Multi-photon entanglement from distant single photon sources on demand

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Abstract

We describe a scheme that allows for the generation of any desired N -photon state *on demand*. Under ideal conditions, this requires only N single photon sources, laser pulses and linear optics elements. First, the sources should be initialised with the help of single-qubit rotations and repeat-until-success two-qubit quantum gates [Lim *et al.*, Phys. Rev. Lett. **95**, 030305 (2005)]. Afterwards, the state of the sources can be mapped onto the state of N newly generated photons whenever needed.

1 Introduction

Photons are natural carriers of quantum information and their states are favoured for a variety of applications. The reason is that photons are very robust against decoherence and possess an ease in distribution. Multi-photon states are therefore the crucial ingredient for quantum cryptography [1], quantum lithography [2] and for experimental tests of quantum mechanics, like the ones performed to rule out local hidden variable theories [3, 4]. Photons are also often used in quantum computing experiments [5, 6]. Most of these applications exploit the quantum correlations that are found in entangled states. In this paper we present a scheme, which can be used to generate *any* desired multi-photon state *on demand* and might lead to a variety of previously unconsidered applications of photon entanglement.

Unfortunately, it is very difficult to create an effective interaction between photons and hence they are difficult to entangle. Photon entanglement is therefore traditionally generated by the means of a single source. The first source of this type was the atomic cascade, which was used for the first test of Bell's inequality [4]. Another example is spontaneous parametric downconversion. It enables the creation of maximally entangled photon pairs and is routinely used in the laboratory [7, 8]. However, the generated entanglement is necessarily probabilistic and can only be detected postselectively. Hence, parametric down conversion does not scale easily and linear optics experiments with more than five photons are extremely challenging [9, 10].

New perspectives for multi-photon experiments arise from recent developments of relatively reliable single photon sources consisting for example of a single atom [11, 12, 13] or a quantum dot [14, 15] placed inside an optical resonator. Using such sources, multi-photon entanglement can be generated with the help of linear optics elements and postselection [16, 17, 18]. However, this approach is not deterministic and results in the destruction of the photons upon detection. Avoiding the latter in postselective schemes would require the use of ready-on-demand entangled multi-photon states as ancillas [19, 20, 6]. One possibility to create multi-photon entanglement in a deterministic manner is to use a single-photon source with a relatively complex level structure and to map the state of the source and operations performed on it subsequently onto the state of newly generated photons [21, 22]. Recently it has been shown by Schön *et al.* [23] that this approach can be used to generate arbitrary multi-photon states on demand.

However, instead of trying to entangle the photons directly, one can also entangle several single photon sources. Once this is done, their state can be mapped on demand onto the states of several newly generated photons whenever needed [24, 25]. In this paper we describe such a scheme and show that it can be used to generate *any* desired N -photon state on demand. Under ideal conditions, this requires only N single photon sources, which can be initialised with the help of single-qubit rotations and repeat-until-success two-qubit quantum gates [26]. Differently from Ref. [24], we focus on the generation of time-bin instead of polarisation-entanglement since this decreases the experimental resource requirements significantly.

The presented scheme has many advantages compared to previous proposals for the generation of arbitrary multi-photon entanglement on demand. As in Refs. [24, 25], we require only single photon sources, passive linear optics elements and detectors *without* photon number-resolution. Nevertheless, we do not rely on the presence of entangled ancilla photons. The required level structure of the sources is simpler than the ones considered in Refs. [23, 21, 22, 24] and has already been tested experimentally (see e.g. Ref. [11]). Moreover, there is no need for a final step disentangling the states of the sources from the states of the photons with the help of measurements and single-qubit rotations as in Ref. [25]. There are also no restrictions on the location of the photon sources, which can be separated from each other by a long distance, since we do not require an explicit interaction between them.

However, the initialisation step requires high photon creation and detection efficiencies since the repeat-until-success two-qubit gate [26] is otherwise not deterministic. In the presence of photon detectors with a finite efficiency the proposed scheme should be used to prepare the sources in a so-called cluster state [27], which can be transformed into any desired state via single-qubit measurements applied to the state of the sources [28, 25]. Alternatively, but less efficiently, the sources could be prepared in a cluster state with the help of the two-qubit quantum gate by Protsenko *et al.* [29] or the entangling scheme by Barrett and Kok [30]. Once the sources have been initialised, it should be possible to create single photons on demand. This process has realistically only a finite success rate but a read-out measurement performed on the state of the respective source can reveal whether a photon has been emitted or not with a very high efficiency [31].

To generate N entangled photons, the scheme requires at least N single-photon sources. However, these sources do not have to be totally identical hence relaxing what would otherwise be a steep experimental requirement. The repeat-until-success quantum gate is constructed such that each emitted photon contributes equally to each photon detection and path fluctuations between the photon sources and the detectors result at most in an overall phase factor with no physical consequences. The experimental setup is therefore *interferometrically stable* and demands only indistinguishability of the sources. The interfering photons do not even need to arrive simultaneously in the detectors as long as they overlap in the setup within their coherence time [32]. To illustrate this point, we start the paper with a discussion of the photon interference experiment by Eichmann *et al.* [33].

2 Photon interference from independent single photon sources

In 1982, Scully and Drühl [34] proposed a simple quantum eraser experiment concerning delayed choice phenomena in quantum mechanics. The setup they considered is shown in Figure 1(a). It consists of two two-level atoms trapped at a fixed distance r from each other. The particles are continuously driven by a resonant laser field and spontaneously emit photons. Each emitted photon causes a click at a certain point on a screen far away from the particles. These clicks, when collected, add up to an interference pattern with a spatial intensity distribution, found also in classical double-slit experiments. This was verified experimentally by Eichmann *et al.* in 1993 [33]. Since then the interpretation of this experiment attracted a lot of interest in the literature [35, 36, 37]. In this section, we give a short description of the above described two-atom double-slit experiment following the discussion by Schön and Beige [37].

The time evolution of the quantum mechanical components, namely the two-level atoms, the surrounding free radiation field and the applied laser light can be modelled with the help of the Schrödinger equation. The role of the applied laser field is to continuously excite the particles. Moreover, the interaction between the atoms and the free radiation field results in the transfer of energy from the excited states of the atoms into the photon modes with wavevector \mathbf{k} and polarisation λ . In other words, the Hamiltonian of the system

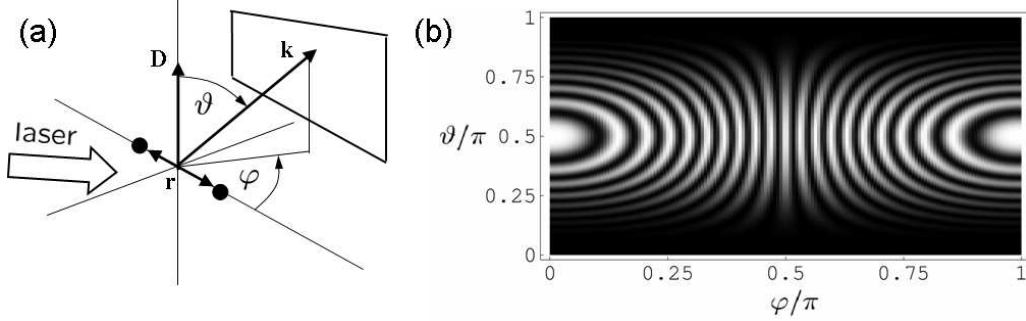


Figure 1: (a) Experimental setup. Two two-level atoms are placed at a fixed distance r from each other. Both are coupled to the same free radiation field and are continuously driven by a resonant laser. This leads to spontaneous photon emissions. Each photon causes a click at a point on a screen. The direction $\hat{\mathbf{k}}$ of the emitted photons is characterized by spatial angles ϑ and φ . (b) Density plot of the emission rate $I_{\hat{\mathbf{k}}}(\rho)$ for two continuously driven two-level atoms. White areas correspond to spatial angles with maximal intensity. For the calculation of this figure, we assumed that the atomic dipole moment \mathbf{D} is perpendicular to the line connecting both atoms [37].

entangles the state of the atoms with the free radiation field, whenever there is some population in the excited state.

However, the setup shown in Figure 1(a) cannot be described by the continuous solution of a Schrödinger equation. To take the possibility of spontaneous photon emissions into account, we also have to consider the environment. The experimental observation of radiating atoms suggests to model the environment by assuming rapidly repeated measurements whether a photon has been emitted or not [38]. In case of a click, the direction $\hat{\mathbf{k}}$ of the emitted photon is registered on the screen. Ref. [37] showed that the state of two atoms prepared in $|\psi\rangle$ is, up to normalisation, of the form

$$|\psi_{\hat{\mathbf{k}}}\rangle \equiv R_{\hat{\mathbf{k}}} |\psi\rangle \quad \text{with} \quad R_{\hat{\mathbf{k}}} = R_{\hat{\mathbf{k}}}^{(1)} + R_{\hat{\mathbf{k}}}^{(2)}. \quad (1)$$

Here $R_{\hat{\mathbf{k}}}^{(i)}$ is the reset operator for the case, in which only atom i is present in the setup, and depends on the position of the respective atom. Eq. (1) ascertains that $R_{\hat{\mathbf{k}}}$ is the sum of the reset operators of two independent atoms. This fact is the origin for the presence of an interference pattern in the two-atom double-slit experiment [33].

We now ask the question, what is the probability density to observe a click in a certain direction $\hat{\mathbf{k}}$. Under the assumption that the atoms are repeatedly prepared in $|\psi\rangle$, this probability density $I_{\hat{\mathbf{k}}}(\psi)$ is given by the norm squared of the state in Eq. (1),

$$I_{\hat{\mathbf{k}}}(\psi) = \| R_{\hat{\mathbf{k}}} |\psi\rangle \|^2. \quad (2)$$

Hence this probability density is of the form

$$\begin{aligned} I_{\hat{\mathbf{k}}}(\psi) &= \| R_{\hat{\mathbf{k}}}^{(1)} |\psi\rangle + R_{\hat{\mathbf{k}}}^{(2)} |\psi\rangle \|^2 \\ &= \| R_{\hat{\mathbf{k}}}^{(1)} |\psi\rangle \|^2 + \| R_{\hat{\mathbf{k}}}^{(2)} |\psi\rangle \|^2 + \langle \psi | R_{\hat{\mathbf{k}}}^{(1)\dagger} R_{\hat{\mathbf{k}}}^{(2)} + R_{\hat{\mathbf{k}}}^{(2)\dagger} R_{\hat{\mathbf{k}}}^{(1)} | \psi \rangle. \end{aligned} \quad (3)$$

This equation shows that the intensity of the light emitted from two atoms is not the same as the sum of the light intensities from two independent atoms (first two terms). The difference is the interference term (third term), which causes the emission of a photon in some directions to be more likely than the emission into others. If one replaces the pure state $|\psi\rangle$ by the stationary state ρ of the atoms in the presence of continuous laser excitation, Eq. (3) can be used to calculate the interference pattern for the experimental setup in Figure

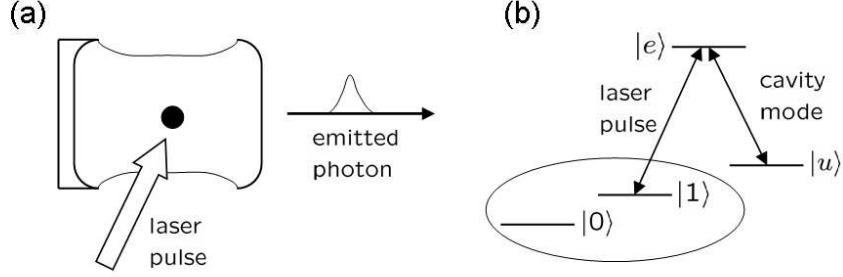


Figure 2: (a) Experimental setup. An external laser pulse drives the atom. The cavity mode decays through the right lossy mirror and a single-photon pulse builds up in the corresponding time-bin. (b) Atomic level structure. The two ground states $|0\rangle$ and $|1\rangle$ define the atomic qubit. Level $|1\rangle$ ($|u\rangle$) and $|e\rangle$ are coupled by a laser (cavity mode), while level $|0\rangle$ is not affected.

1(a). The result is shown in Figure 1(b) and agrees well with the observation in the experiment by Eichmann *et al.* [33].

The coupling between the atoms and the free radiation field results in the transfer of energy into the free radiation field. In general, there is less than one excitation in each mode (\mathbf{k}, λ) of the free radiation field. The interference pattern stems from the wave behaviour of these excitations prior to the detection of a photon. Note that a *single photon* does not exist until it is actually detected on the screen. Quantum mechanics tells us that the observations on the screen always result in the detection of an integer number of photons. Moreover, each detected photon is created by both atoms and leaves a trace in and contains information about all its respective sources.

3 An entangling two-qubit gate operation between distant single photon sources

In the following, we use the possibility of strong correlations between emitted photons and the state of their respective sources to process quantum information efficiently. More concretely, we consider single photon sources consisting of an atom-like system with a Λ -level configuration trapped inside a resonant optical cavity (c.f. Figure 2). To generate a single photon on demand, a laser pulse with a relatively slowly increasing Rabi frequency should be applied. Such a pulse transfers an atom initially prepared in $|1\rangle$ via an adiabatic passage into $|u\rangle$, thereby placing one photon into the cavity [11, 12]. From there it leaks out through the outcoupling mirror. Repumping the atom afterwards into its initial state results in the overall operation

$$|1\rangle \longrightarrow |1; 1_{\text{ph}}\rangle. \quad (4)$$

The role of the cavity is to fix the direction of the spontaneously emitted photon so that it can be easily processed further.

Suppose each atom within a large network of single photon sources contains one qubit consisting of the two ground states $|0\rangle$ and $|1\rangle$ (c.f. Figure 2). Then it is possible to generate a single photon on demand such that its state depends on the initial state of the atom and

$$\alpha |0\rangle + \beta |1\rangle \longrightarrow \alpha |0; \text{E}\rangle + \beta |1; \text{L}\rangle. \quad (5)$$

Here $|\text{E}\rangle$ denotes an *early* and $|\text{L}\rangle$ denotes a *late* photon. One way to implement the encoding step (5) is to first swap the atomic states $|0\rangle$ and $|1\rangle$. Next a laser pulse with increasing Rabi frequency should be applied to perform the operation (4). Afterwards, the states $|0\rangle$ and $|1\rangle$ should be swapped again and the photon generation process (4) should be repeated at a later time. In the final state (5), the qubit is double encoded

in the state of the source as well as in the state of the photon. The encoding (5) is the main building block for the realisation of a deterministic entangling gate operation between two qubits. It requires the simultaneous generation of a photon in each of the involved single photon sources. Afterwards, the photons should pass, within their coherence time, through a linear optics network which performs a photon pair measurement on them.

Suppose, the two qubits involved in the gate operation are initially prepared in the arbitrary two-qubit state

$$|\psi_{\text{in}}\rangle = \alpha |00\rangle + \beta |01\rangle + \gamma |10\rangle + \delta |11\rangle. \quad (6)$$

Using Eq. (5), we see that the state of the system equals in this case

$$|\psi_{\text{enc}}\rangle = \alpha |00; \text{EE}\rangle + \beta |01; \text{EL}\rangle + \gamma |10; \text{LE}\rangle + \delta |11; \text{LL}\rangle \quad (7)$$

after the creation of the photons. If a photon pair measurement afterwards results in the detection of a state of the form

$$|\Phi\rangle = |\text{EE}\rangle + e^{i\varphi_1} |\text{EL}\rangle + e^{i\varphi_2} |\text{LE}\rangle + e^{i\varphi_3} |\text{LL}\rangle, \quad (8)$$

then the state of the photon sources is projected onto

$$|\psi_{\text{fin}}\rangle = \alpha |00\rangle + e^{-i\varphi_1} \beta |01\rangle + e^{-i\varphi_2} \gamma |10\rangle + e^{-i\varphi_3} \delta |11\rangle. \quad (9)$$

This state differs from the one in Eq. (6) by a unitary operation, namely a two-qubit phase gate. As we see below, if the state (8) is a maximally entangled state, this operation is a phase gate with maximum entangling power.

Performing a deterministic gate operation requires a complete set of basis states with each of them being of the form (8). Such a basis is called mutually unbiased [39], since its observation does not reveal any information about the coefficients α , β , γ and δ . The limitation of linear optics is that it is not possible to perform a complete Bell measurement [40]. At most two maximally entangled photon states can be distinguished using only available linear optics elements. We therefore consider in the following a measurement of the basis states [26]

$$|\Phi_{1,2}\rangle = \frac{1}{\sqrt{2}} (|x_1 y_2\rangle \pm |y_1 x_2\rangle), \quad |\Phi_3\rangle = |x_1 x_2\rangle, \quad |\Phi_4\rangle = |y_1 y_2\rangle \quad (10)$$

with

$$|x_{1,2}\rangle \equiv \frac{1}{\sqrt{2}} (|E\rangle + |L\rangle), \quad |y_1\rangle \equiv \frac{1}{\sqrt{2}} (|E\rangle - |L\rangle), \quad |y_2\rangle \equiv i |y_1\rangle. \quad (11)$$

This definition implies

$$\begin{aligned} |\Phi_{1,2}\rangle &= \pm \frac{1}{2} e^{\pm i\pi/4} (|\text{EE}\rangle \mp i |\text{EL}\rangle \pm i |\text{LE}\rangle - |\text{LL}\rangle), \\ |\Phi_3\rangle &= \frac{1}{2} (|\text{EE}\rangle + |\text{EL}\rangle + |\text{LE}\rangle + |\text{LL}\rangle), \quad |\Phi_4\rangle = \frac{1}{2} i (|\text{EE}\rangle - |\text{EL}\rangle - |\text{LE}\rangle + |\text{LL}\rangle). \end{aligned} \quad (12)$$

A comparison with Eq. (8) shows that these $|\Phi_i\rangle$ are indeed mutually unbiased. To find out which quantum gate operation belongs to which measurement outcome $|\Phi_i\rangle$, we write the encoded state (7) as

$$|\psi_{\text{enc}}\rangle = \frac{1}{2} \sum_{i=1}^4 |\psi_i\rangle |\Phi_i\rangle \quad (13)$$

and find that

$$|\psi_{1,2}\rangle = \pm e^{\mp i\pi/4} Z_1 (\pm \frac{1}{2}\pi) Z_2 (\mp \frac{1}{2}\pi) U_{CZ} |\psi_{\text{in}}\rangle, \quad |\psi_3\rangle = |\psi_{\text{in}}\rangle, \quad |\psi_4\rangle = -i Z_1(\pi) Z_2(\pi) |\psi_{\text{in}}\rangle \quad (14)$$

with

$$Z_i(\varphi) \equiv \text{diag}(1, e^{-i\varphi}), \quad U_{CZ} \equiv \text{diag}(1, 1, 1, -1). \quad (15)$$

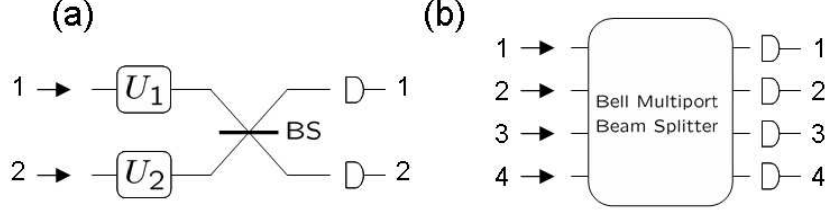


Figure 3: Two possible experimental setups for the realisation of the photon pair measurement in a mutually unbiased basis.

Here $Z_i(\varphi)$ describes a one-qubit phase gate that changes the phase of an atom if it is prepared in $|1\rangle$ and U_{CZ} denotes a controlled two-qubit phase gate with maximum entangling power. The above equations show that a measurement of $|\Phi_1\rangle$ or $|\Phi_2\rangle$ results with probability $1/2$ in the completion of the universal phase gate U_{CZ} up to local operations, which can be undone easily. A measurement of $|\Phi_3\rangle$ or $|\Phi_4\rangle$ yields the initial qubits up to local operations. Since the quantum information stored in the system is not lost at any stage of the computation, the above described steps can be *repeated until success*. On average, the completion of one repeat-until-success quantum gate requires two repetitions.

Let us now comment on the experimental feasibility of the proposed two-qubit gate. One way to realise the above described photon pair measurement is to convert the time bin encoding of the photonic qubits into a polarisation encoding. It is known that sending two polarisation encoded photons through a beam splitter results in a measurement of the states $|\text{hv} \pm \text{vh}\rangle$, $|\text{hh}\rangle$ and $|\text{vv}\rangle$. Measuring the states $|\Phi_i\rangle$ therefore only requires passing the photons through a beam splitter after applying the mapping $U_i = |\text{h}\rangle\langle\text{x}_i| + |\text{v}\rangle\langle\text{y}_i|$ on the photon coming from source i with $|x_i\rangle$ and $|y_i\rangle$ as in Eq. (11). This is illustrated in Figure 3(a). Figure 3(b) shows an alternative approach in which the time bin encoded photons are sent through a Bell multiport beam splitter. An early (late) photon from source 1 should enter input port 1 (3) and an early (late) photon from source 2 should enter input port 2 (4). More details can be found in Refs. [26, 27].

4 The initialisation of the sources

For the initialisation of the photon sources we combine the two-qubit phase gate from above with single-qubit rotations, achieved by standard quantum optics techniques as routinely employed in ion trap experiments [41, 42]. They constitute a universal set of gates and can therefore be used to prepare N single photon sources in any desired entangled state [43]. Especially easy to prepare are N -qubit states that belong to the class of two-dimensional matrix-product states. They can be generated using only $N - 1$ two-qubit gate operations between “neighbouring” sources, since they can always be written as

$$|\psi\rangle = V_{N-1} \dots V_1 |i_1, \dots, i_N\rangle. \quad (16)$$

Here $|i_n\rangle$ is a one-qubit state and V_n is a two-qubit quantum gate acting on qubit n and qubit $n + 1$. Which operations V_n have to be applied in order to prepare a certain final state is described in detail in Ref. [44]. Familiar examples of two-dimensional matrix-product states are W states, GHZ states and, most importantly, one-dimensional cluster states [45]. To generate a one-dimensional cluster state, the V_n are the controlled-phase gates U_{CZ} defined in Eq. (15) if the single photon sources are initially all prepared in $|i_n\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$ [28].

5 The generation of multi-photon entanglement on demand

Once the atomic qubits have been initialised, N photons in exactly the same state can be created by simply mapping the state of the sources onto the state of N newly generated photons. This can be done whenever

required, since the atoms act as perfect single photon storage devices. The steps involved in this mapping process are similar to the steps involved in the generation of an encoded photon (5) and can be realised using exactly the same atomic level configuration (c.f. Figure 2(b)). Suppose the state of a single photon source equals

$$|\psi_{\text{at}}\rangle = \alpha |0\rangle + \beta |1\rangle. \quad (17)$$

To generate a photon in the same state, a single-qubit rotation should be applied that exchanges the states $|0\rangle$ and $|1\rangle$. Afterwards a laser pulse transfers the state $|1\rangle$ into the state $|u\rangle$, thereby resulting in the generation of an *early* photon. Finally, another exchange of the states $|0\rangle$ and $|1\rangle$ and the creation of a *late* photon conditional on the atom being in state $|1\rangle$ results in the overall operation

$$|\psi_{\text{at}}\rangle \rightarrow \alpha |u; \text{E}\rangle + \beta |u; \text{L}\rangle. \quad (18)$$

The final state is a state with the atom in $|u\rangle$ and a single photon in

$$|\psi_{\text{ph}}\rangle = \alpha |\text{E}\rangle + \beta |\text{L}\rangle. \quad (19)$$

The state of the atom has indeed been mapped onto the state of a newly generated photon.

The mapping of the state of N independent single photon sources onto N newly generated photon can be done in exactly the same way. Instead of generating a photon from only one source, photons should be created in each of the prior initialised sources. Given the atoms are initially prepared in the state

$$|\psi_{\text{at}}\rangle = c_{0\dots 0} |0\dots 0\rangle + c_{0\dots 01} |0\dots 01\rangle + \dots + c_{1\dots 1} |1\dots 1\rangle, \quad (20)$$

this results in the generation of the multi-photon state

$$|\psi_{\text{ph}}\rangle = c_{0\dots 0} |\text{E}\dots \text{E}\rangle + c_{0\dots 01} |\text{E}\dots \text{EL}\rangle + \dots + c_{1\dots 1} |\text{L}\dots \text{L}\rangle, \quad (21)$$

while the atoms all end up in $|u\rangle$. Here we did nothing else, than replacing the states $|0\rangle$ and $|1\rangle$ in Eq. (20) by the single photon states $|\text{E}\rangle$ and $|\text{L}\rangle$. As mentioned before, the state of the newly generated photons is exactly the same as the initial state of the N single photon sources.

6 Conclusions

We described a scheme that allows for the generation of any desired entangled N -photon state on demand. Under ideal conditions, the scheme requires only N single photon sources and passive linear optics elements. If necessary, linear optics can also be employed to transform the time-bin encoded photons into polarisation encoded ones. The basic idea is to first prepare the single photon sources in the desired state. Afterwards their state can be mapped onto the state of N newly generated photons whenever needed.

The initialisation of the sources can be achieved using single-qubit rotations and the repeat-until-success quantum computing scheme by Lim *et al.* [26], which results in the realisation of an eventually deterministic entangling two-qubit phase gate upon the application of a carefully chosen photon pair measurement. In order to elucidate the underlying physical mechanism, we recalled a recent discussion about interference in the fluorescence of two laser-driven non-interacting atoms [37]. We also pointed out, that our scheme is especially efficient when engineering two-dimensional matrix-product states, such as W -states, GHZ states and one-dimensional cluster states [44].

Considering recent advances on single photon sources and detectors, the two most important ingredients in our scheme, raises hope that an experimental realisation will soon be feasible. When using photon detectors with finite efficiencies and when the photon generation is not ideal, the repeat-until success quantum gate becomes probabilistic. However, the proposed scheme can still be used to generate multi-photon entanglement on demand. The reason is that even probabilistic quantum gates can be used to prepare the sources efficiently in a so-called cluster state [30, 27], which can then be transformed into the desired state using single-qubit measurements on the states of the sources [28]. Whether a photon has been generated in

a certain source or not can be detected afterwards by measuring whether the source is prepared in the state $|u\rangle$ or not (c.f. Figure 2(b)).

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